Diode-pumped narrow linewidth multi-kW metalized Yb fiber amplifier

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Abstract: We investigate high brightness pumping of a multi-kW Yb fiber amplifier in a bi-directional pumping configuration. Each pump outputs 2 kW in a 200 μm, 0.2 NA multi-mode fiber. Gold-coated specialty gain fibers, with 17 μm MFD and 5-dB/meter pump absorption, have been developed. The maximum fiber amplifier output power is 3.1 kW, limited by multi-mode instability, with 90% O-O efficiency 12 GHz Linewidth and M2 < 1.15.
OCIS codes: (140.3510) Lasers, fiber; (140.3615) Lasers, ytterbium; (060.2430) Fibers, single-mode.

1. INTRODUCTION

Yb-doped fiber laser has experienced exponential growth over the past decade. The output power of a cw Yb fiber laser is limited by stimulated Raman scattering (SRS), as is evident from [1]. Increasing fiber modal area can overcome SRS limitation but makes the fiber significantly more susceptible to multi-mode instability (MMI) [2], thus degrading the beam quality of the fiber laser output. Fiber laser power can also be extended via beam combining techniques [3]. Because beam-combinable fiber amplifier requires narrow linewidth, its power is limited by stimulated Brillouin scattering (SBS). Increasing fiber modal area can overcome SBS limitation but makes the fiber significantly more susceptible to MMI, rendering such fibers unsuitable for beam combining [3].

In addition to increasing the fiber modal area, reducing the fiber length is another route to reducing overall fiber nonlinearity for SRS and SBS suppression. Shortening active fiber length while maintaining overall pump absorption for constant modal area requires higher Yb-doping and/or smaller pump clad. Of the two approaches, rapid improvement in pump brightness makes reducing pump clad a viable option. Over 300 W output power in a 100-μm, 0.22 NA fiber-coupled diode has been reported [4]. Moreover, WBC technique [5] can multiply this pump brightness.

In the case of a short active fiber, thermal management becomes a main challenge. In addition to acrylate coating damage, dn/dT effect becomes significant at high heat loads and modifies fiber refractive index profile (RIP) [6]. Fig. 1 shows quantum-defect heat-load deposition along the length of a bi-directionally pumped 3-kW fiber amplifier similar to the fiber amplifiers investigated in this work. The peak heat loads, in excess of 150 W/m, are near the two fiber ends where the pumps are coupled. Solving the heat equation for a cylindrical fiber shows that dn/dT due to peak heat load is a significant fraction of the core/clad index difference (Δn). An increase in Δn between fiber core and cladding increases fiber NA, reduces higher-order-mode (HOM) suppression and lowers the MMI threshold.

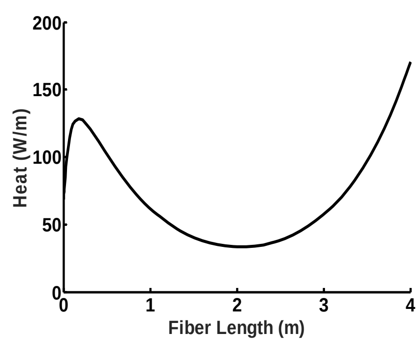

Fig. 1 Sample heat load along fiber amplifier length for bi-directional pumping.

Fig. 2 shows modeled HOM (LP11) loss for a fiber of the same type as the ones used in this Letter. Because our main interest is in the regime with high heat load, we add dn/dT to the fiber RIP and compute HOM loss based on this modification. Comparing to the room temperature case (0W/m heat load), addition of 150W/m heat load to the fiber degrades LP11 loss by > 100dB. Thus, as fiber amplifier output increases, its HOM suppression degrades and eventually MMI sets in. LP11 loss can be used to predict the onset of MMI in the regime where effects due to high heat load

dominate. According to previous studies [2], HOM experiences very high gain over short interaction length once MMI sets in. Therefore we use the peak heat load in the fiber amplifier when accounting for dn/dT effects. Based on experiences at various organizations [7], we select 35dB/m HOM loss as MMI threshold for our fiber design.

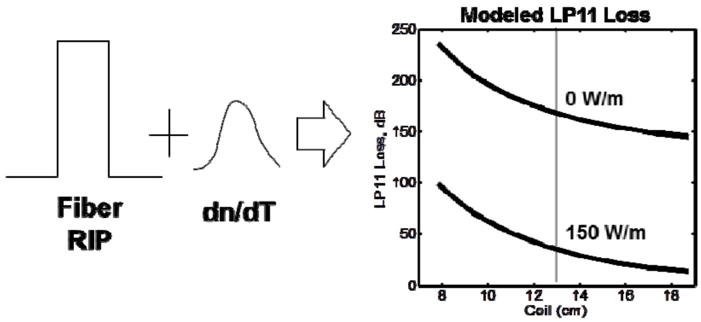

Fig 2. Calculated LP11 loss at 0 W/m and 150 W/m heat load for one OFS fiber.

2. EXPERIMENT

The experimental setup is shown in Fig. 3. The 976-nm pump lasers are prototypes from Teradiode Inc. Each pump outputs 2 kW in a 200-µm, 0.2 NA delivery fiber. Over 90% of the power is within +/-2nm of 976 nm. Such record pump brightness is achieved by incorporating WBC technology [5]. The fiber power amplifier is bi-directionally pumped using dichroic mirrors. The seed wavelength is 1066 nm and is spectrally broadened using an electro-optic phase modulator for SBS suppression. The broadened optical seed is amplified with IPG pre-amplifiers to achieve output power up to 50 W before it was sent into our fiber amplifier for kW+ output power. The fiber amplifier output is coupled out using the counter-pump dichroic mirror and routed into the diagnostics. In addition to power meter, PER measurement, M^2 meter, CCD beam imager we also use a fiber to measure the on-axis intensity to detect the onset of MMI.

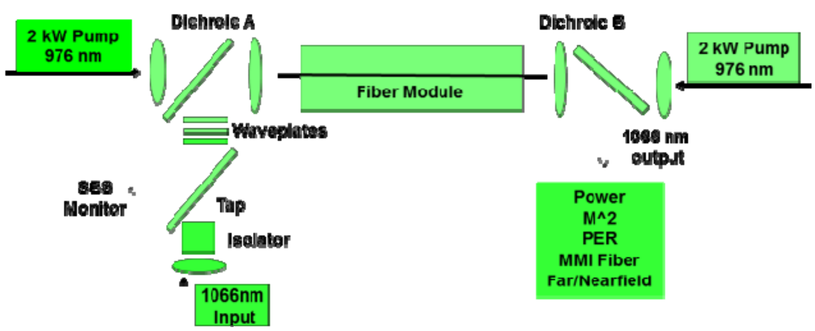

Fig. 3 Experimental Setup.

A triple-clad fiber with 17-µm mode field diameter (MFD) is investigated. The fiber design principle can be found in [8]. Our fiber amplifier uses 4 meters of active fiber for 20 dB total pump absorption. The fiber has gold coating outside of its F-doped outerclad. Gold coating can operate at significantly higher temperature and provides a thermal ground so that the overall fiber amplifier temperature is lowered.

HOM losses are computed based on the sum of measured fiber RIP and modeled dn/dT effects. Fig. 4 shows the LP11 loss as a function of heat load. HOM loss is >700 dB/m at room temperature but is reduced to ~35 dB/m with a heat load of 170 W/meter. This corresponds to the peak heat load for the counter-pumped fiber amplifier case with 1.7 kW of output power. Experiment confirmed 1.7 kW as MMI power threshold. The MMI threshold for the co-pump case is similar to the counter-pump case. The MMI threshold nearly doubles with bi-directional pumping, to 3.2 kW. Fig. 5a shows the pump vs. output for bi-directional pumping. The O-O efficiency is 90% up to 3.1 kW and M^2 is < 1.15 at 3 kW. Without active polarization control, the output PER is 10 dB. Fig. 5b shows the spectrum containing both backward Raleigh and SBS signals at 3 kW. With a 12.5 GHz signal, the SBS signal is slightly below the Rayleigh backscatter.

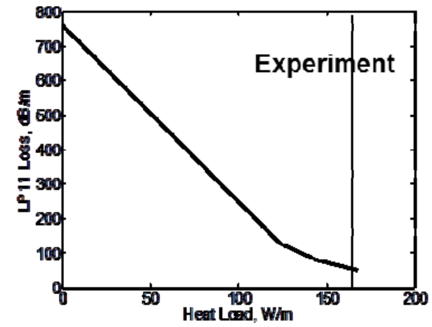

Fig 4. Modeled LP11 loss as a function of fiber peak heat load at 13-cm coil diameter for second fiber. Experiment verified our design rule of using 35 dB/m HOM loss as MMI threshold.

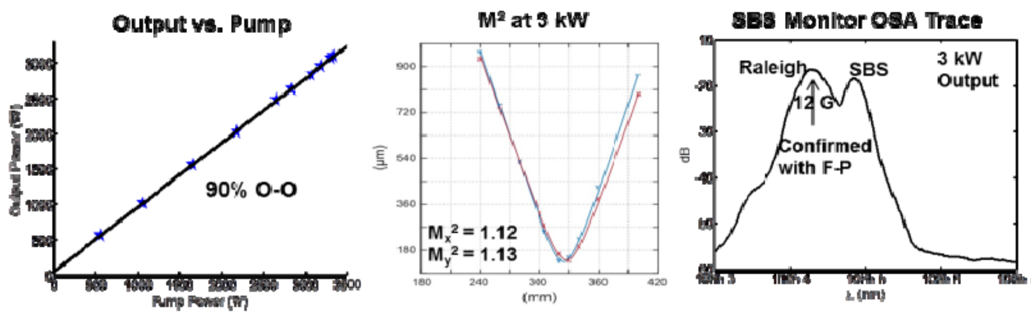

Fig 5. Experimental results using Yb triple-clad fiber (a) Pump vs. output for bi-directional pumping and M2 at 3 kW (b) Backward Raleigh scattering and SBS at 3 kW.

3. CONCLUSION

In summary, we have demonstrated a linearly polarized, diffraction-limited 3.1-kW fiber amplifier with 90% O-O efficiency and 12 GHz linewidth. This achievement is enabled by utilizing short active fiber with record brightness 976-nm pump lasers. We devised a design rule for MMI-free operation in the high heat load regime. This simple design rule is validated with specialty fiber that can operate MMI-free with 170 W/m of heat load. The ability to handle such high heat load allows future multi-kW power scaling with direct diode pumping at 976 nm.

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